Improved quadrupling photonic millimeter-wave generation and RoF transmission without optical filtering

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Based on parallel Mach-Zehnder Modulators (PMZM), an optimized scheme for improving the generation of frequency quadrupling photonic millimeter-wave is proposed. In the designed scheme, by optimizing unbalanced modulation indices of each MZM, high-quality photonic millimeter-wave was still generated under non-ideal actual MZM condition. The feasibility of the proposed scheme is verified by theoretical analysis and simulation experiment. With the proposed approach, both the optical sideband suppression ratio (OSSR) and RF spurious suppression ratio (RSSR) of the generated photonic millimeter-wave have been enhanced, and the receiver sensitivity of the corresponding Radio over Fiber (RoF) transmission system has also been optimized.

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1. Introduction

Millimeter-wave (MM-wave) communication emerged as a powerful technique with the demand and rapid development of broadband wireless access (BWA) networks. Owing to extremely high transmission loss, the coverage range of high-frequency millimeter waves is greatly limited. Thanks to huge bandwidth and low transmission loss provided by optical fiber and flexible access provided by wireless communication, the radio-over-fiber (RoF) technology at millimeter-wave bands is a promising solution to providing broadband service, long transmission distance, wide coverage, and mobility [1,2]. Moreover, Millimeter waves in the 60 GHz band have attracted much attention because they can provide 7 GHz unauthorized bandwidth.

To realize a broadband agile RoF system, the cost-effective photonic generation of high quality 60 GHz and beyond millimeter-wave is a key factor [3-6]. The generation of photonic millimeter waves by frequency multiplication can significantly reduce the bandwidth requirements of electro-optic modulators and transmitter drive circuits. Various photonic millimeter-wave generation methods based on frequency multiplication have been developed so far, including dual laser sources based optical heterodyning, mode-locked fiber lasers, and external electro-optic modulation [7-10]. Among these methods, external modulation based on the $LiNbO_3$ Mach-Zehnder modulator (MZM) has been considered an attractive approach due to its stability and simplicity. In addition, in the practical application of WDM-RoF systems, optical filters should be avoided as they will significantly increase the cost and complexity of the system. Several schemes for generating quadrupling photonic millimeter-wave are proposed [11-13]. Nevertheless, the residual chirp accompanied by the limited extinction ratio (EXT) of non-ideal MZM modulators and its effects on the generated quadrupling photonic millimeter-wave have not been deeply analyzed.

In this manuscript, without optical filtering, frequency quadrupling photonic millimeter-wave generation scheme based on parallel MZMs (PMZM) was presented. The limited EXT of actual commercial MZM was taken into consideration, and unbalanced driving signal of each arm of MZM was utilized to counteract the adverse effects brought by the limited EXT. Under the practical non-ideal MZM condition, the optical sideband suppression ratio (OSSR) and RF spurious suppression ratio (RSSR) of the generated photonic millimeter-wave were analyzed. Moreover, the transmission performance of the 2.5 Gb /s RoF system in the 60 GHz band was studied.

2. Principle

Fig. 1 plots the proposed diagram of PMZM (MZM1 and MZM2) based generation scheme for frequency quadrupling photonic millimeter-wave signal. The output lightwave $E_0 e^{j\omega_0 t}$ from laser diode (LD) is injected into the PMZM, ω_0 and E_0 are angular frequency and amplitude of the optical carrier, respectively. The PMZM are driven by millimeter-wave signal from microwave signal generator (MSG), and the phase difference between the driving signals of the two sub-modulators MZM1 and MZM2 is π. Both MZM1 and MZM2 are biased at the minimum transmission point. A π/2 phase shift is applied between driving signals of the upper and lower arms of each MZM, and the amplitudes of the driving signals are adjusted by the electrical gain (EG) element.

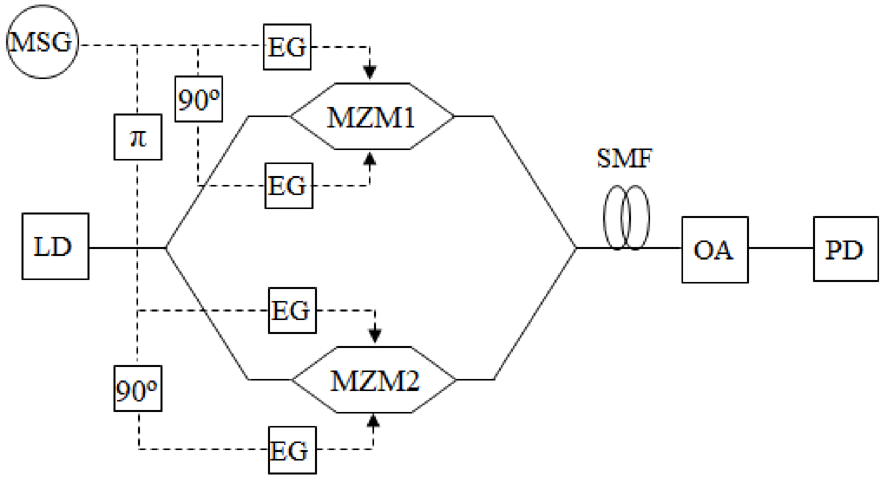


Fig. 1. Diagram of the proposed quadrupling photonic millimeter-wave generation. LD: laser diode; MSG: microwave signal generator; EG: electrical gain; MZM: Mach-Zehnder modulator; SMF: single mode fiber; OA: Optical amplifier; PD: photo diode

The driving voltages of the two arms of MZM1 can be represented as $V_{11}(t)=V_{m1}\sin 2\pi f_m t+V_\pi$ and $V_{12}(t)=V_{m2}\sin(2\pi f_m t+\pi/2)$, and the driving voltages of the two arms of MZM2 can be indicated as $V_{21}(t)=V_{m1}\sin(2\pi f_m t+\pi)+V_\pi$ and $V_{22}(t)=V_{m2}\sin(2\pi f_m t+3\pi/2)$. Where V_m and f_m are amplitude and frequency of driving millimeter-wave signal, respectively. V_π is the half-wave voltage of each MZM. Therefore, the output optical field from MZM1 and MZM2 can be expressed respectively as

$$
\begin{aligned}
E_1(t) &= \frac{E_i}{4} e^{j2\pi f_c t}\left[e^{j\frac{\pi V_{m1}\sin 2\pi f_m t+V_\pi}{V_\pi}} + e^{j\frac{\pi V_{m2}\sin(2\pi f_m t+\frac{\pi}{2})}{V_\pi}}\right] \\
&= \frac{E_i}{4} e^{j2\pi f_c t}\sum_{n=-\infty}^{\infty} e^{jn2\pi f_m t}[-J_n(m_1)+\gamma J_n(m_2)j^n]
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
E_2(t) &= \frac{E_i}{4} e^{j2\pi f_c t}\left[e^{j\frac{\pi V_{m1}(2\pi f_m t+\pi)+V_\pi}{V_\pi}} + e^{j\frac{\pi V_{m2}\sin(2\pi f_m t+\frac{3\pi}{2})}{V_\pi}}\right] \\
&= \frac{E_i}{4} e^{j2\pi f_c t}\sum_{n=-\infty}^{\infty} e^{jn(2\pi f_m t+\pi)}[-J_n(m_1)+\gamma J_n(m_2)j^n]
\end{aligned}
\tag{2}
$$

where $m_{1,2}=\pi V_{m1,2}/V_\pi$ is modulation index of the two arms of each MZM, $V_{m1,2}$ is the driving signal amplitude of the two arms of each MZM. γ is a scaling factor between 0 and 1 that accounts for a non-ideal MZM, and the parameter is related to the EXT ε by $\gamma=(\sqrt{\varepsilon}-1)/(\sqrt{\varepsilon}+1)$. $J_n(x)$ is the n order Bessel function of the first kind.

As a consequence, the output photonic millimeter-wave of the PMZM could be written as

$$
\begin{aligned}
E_o(t) &= E_1(t)+E_2(t) \\
&= \frac{E_i}{4} e^{j2\pi f_c t}\sum_{n=-\infty}^{\infty} e^{jn2\pi f_m t}[-J_n(m_1)+\gamma J_n(m_2)j^n][1+(-1)^n] \\
&= \frac{E_i}{4} e^{j2\pi f_c t}\sum_{n} A_n e^{jn2\pi f_m t}
\end{aligned}
\tag{3}
$$

From the above formula, it can be deduced that the amplitude of the nth-order sideband of the output signal is

$$
A_n=[-J_n(m_1)+\gamma J_n(m_2)j^n][1+(-1)^n]=\begin{cases} 2[-J_n(m_1)+\gamma J_n(m_2)], & n=4k \\ -2[J_n(m_1)+\gamma J_n(m_2)], & n=4k+2 \\ 0, & n=2k+1 \end{cases}
\tag{4}
$$

When the EXT of an ideal MZM modulator is infinite (ε = ∞, γ = 1), and the modulation indices of the upper and lower arms are equal ($m_1=m_2=m$), the carrier component is eliminated ($\gamma J_0(m)-J_0(m)=0$), and the output of the PMZM modulator is + 2nd order and -2 order sideband. Under square law detection, beating between + 2nd order and -2 order sidebands will generate quadrupling millimeter-wave signal at the output of the photo diode (PD).

However, the EXT of actual commercial MZM is limited, and unwanted carrier components will be generated at the output of PMZM. Which will lead to the deterioration of the quality of the generated quadrupling photonic millimeter-wave and the decline of corresponding RoF transmission performance. Through optimizing the modulation indices m_1 and m_2 of the commercial MZM, the amplitude A_0 of the optical carrier component could be made as close as possible to zero, thereby suppressing or even eliminating the carrier component.

To eliminate the unwanted optical carrier component at the output of the PMZM, the modulation indices m_1 and m_2 of each MZM need to meet the following conditions

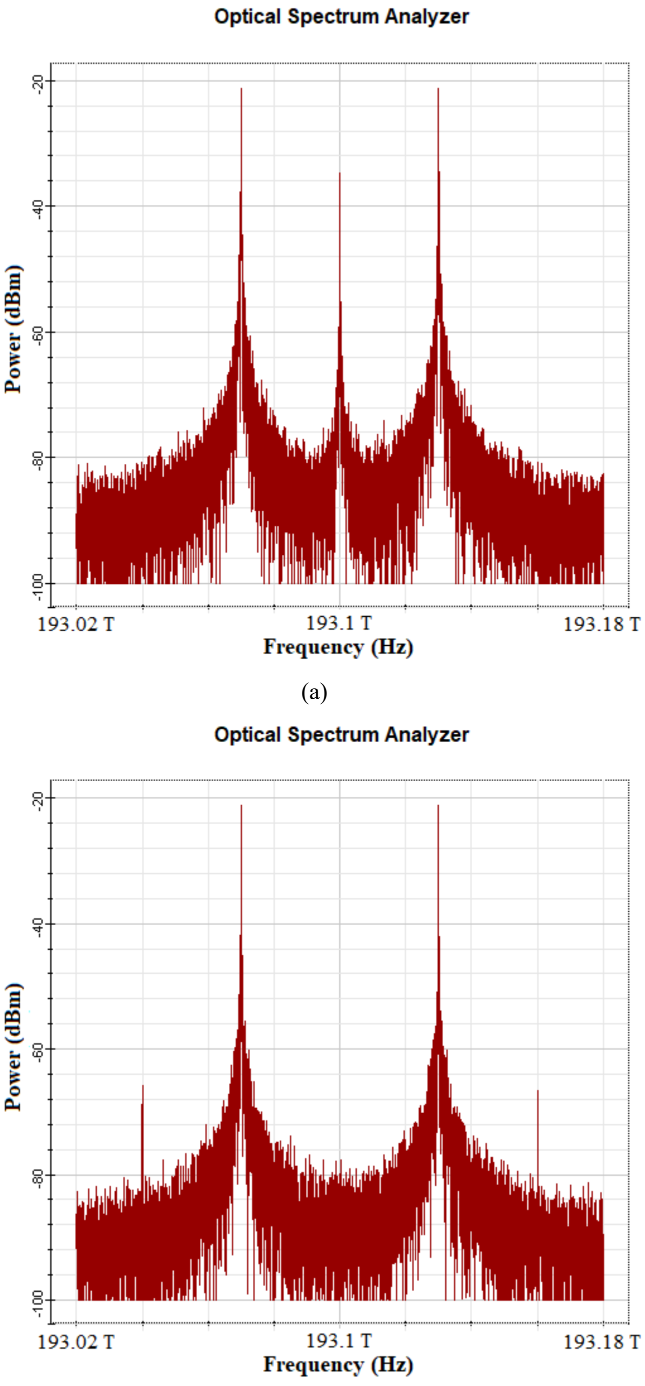
$$(\sqrt{\varepsilon}+1)J_0(m_1)=(\sqrt{\varepsilon}-1)J_0(m_2) \tag{5}$$

When the EXT of a commercial MZM modulator is given, the optimal modulation indices m_1 and m_2 of each MZM can be determined through numerical calculation based on the above formula. For example, the typical EXT of a commercial MZM is 30 dB, then m_1 = 1.055 and m_2 = 0.945 could be obtained.

3. Results and discussion

To examine the effectiveness of the improved quadrupling photonic millimeter-wave generation scheme plotted in Fig. 1, simulation based on commercial software OptiSystem was conducted, and the simulation parameters were the same as the theoretical values. The output lightwave frequency of LD and driving millimeter-wave signal frequency applied to MZM is 193.1 THz and 15 GHz, respectively. EXT and half-wave voltage of each MZM is 30 dB and 4 V, respectively. The identical modulation index m_1 and m_2 of each MZM is set to be 1 in the traditional scheme, while the modulation index m_1 and m_2 is optimized to be 1.055 and 0.945 in the optimized scheme, respectively. Oscilloscope visualizer and Radio frequency (RF) spectrum analyzer are employed to observe optical spectrum and RF spectrum and of the generated quadrupling photonic millimeter-wave signal, respectively.

Fig. 2 shows optical spectrum of quadrupling photonic millimeter-wave generated by two schemes based on PMZM without optical filtering. It can be found clearly that both traditional and optimized scheme can generate a photonic millimeter-wave composed of two major 2nd order sidebands with a frequency interval of 60 GHz, the interval is four times of driving millimeter-wave signal frequency. As can be seen from Fig. 2(a), with traditional scheme, optical carrier component could not be ignored and optical sideband suppression ratio (OSSR) is only around 14 dB. This is due to the influence of the limited EXT of the non-ideal MZM. While in the optimized scheme shown in Fig. 2(b), optical carrier component has been almost completely eliminated through optimization of the unbalanced modulation indices m_1 and m_2, and OSSR is about 45 dB.

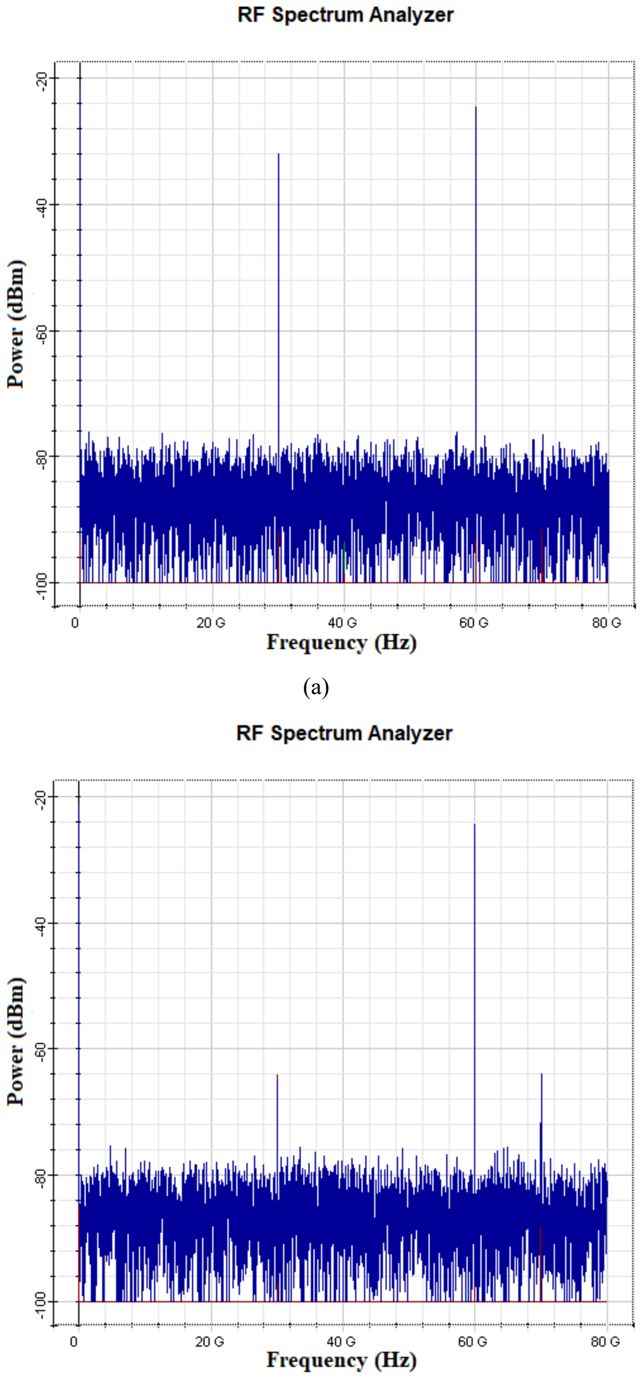


(a)

(b)

Fig. 2. Optical spectrum of the generated quadrupling photonic millimeter-wave signal, ε = 30 dB. (a) Traditional scheme and (b) optimized scheme (colour online)

At the receiver, a square law PD of 0.8 A/ W responsivity, 10 nA dark current, and 1e-22 W/ Hz thermal power density is utilized to detect the received signal. The radio frequency (RF) spectrum of the generated frequency quadrupling millimeter-wave is shown in Fig. 3. The RF spectrum mainly consists of the 60 GHz target harmonic and the undesired sidebands. As can be seen from Fig. 3(a) and Fig. 3(b), the RF spurious suppression ratio (RFSSR) of the generated millimeter-wave is only around 7.8 dB in the traditional scheme, whereas in the optimized scheme, the RSSR is increased to about 39.8 dB.



(a)

(b)

Fig. 3. RF spectrum of the generated quadrupling millimeter-wave signal, ε =30 dB. (a) Traditional scheme and (b) optimized scheme (colour online)

To estimate the transmission performance of the PMZM based quadrupling RoF system, a 2.5 Gbit/s NRZ data is modulated on the generated photonic millimeter-wave by employing an intensity modulator. The RoF transmission line is a single mode fiber (SMF) of 50 Km, with a dispersion coefficient of 16.75 ps/nm/km and an attenuation coefficient of 0.2 dB/ km. An optical amplifier with the gain of 20 dB is adopted to compensate the loss of the RoF link. The detected signal at the output of PD goes through an electrical Gaussian band pass filter (BPF) with a bandwidth of 1.5 times the data rate. After that, the signal is down converted by using an RF local oscillator (LO) and an electrical mixer. The demodulated data is filtered through an electrical low pass filter (LPF) and then imported into a bit-error-rate (BER) analyzer.

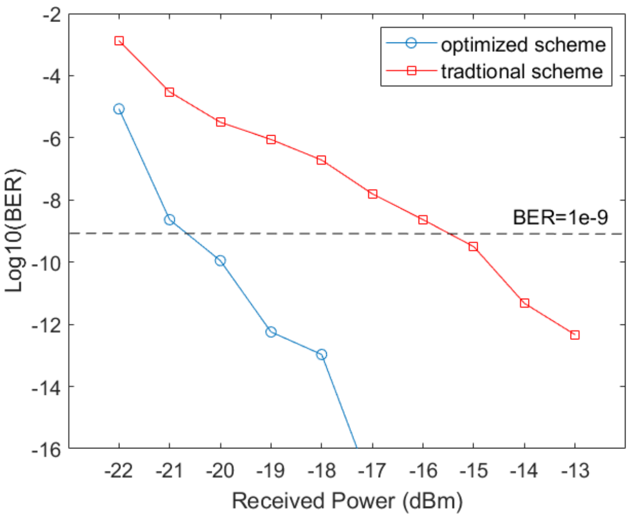


Fig. 4. BER performance of the quadrupling RoF link, L=50 Km (colour online)

The BER curve of the quadrupling RoF link is shown in Fig. 4, both traditional and optimized schemes are evaluated. To achieve a BER of 10^{-9} after 50 Km SMF transmission, the receiver sensitivity is about −15.6 dBm in the traditional scheme. While for the optimized scheme, the corresponding receiver sensitivity is about −20.8 dBm. Which means that by setting the unbalanced modulation indices of the non-ideal MZM to the optimal values, the receiver sensitivity could be optimized approximately 5.2 dB.

4. Conclusion

For photonic generation of frequency quadrupling millimeter-wave based on PMZM without optical filtering, unbalanced MZM modulation indices optimization is proposed to improve system performance. The impact of imperfect EXT of MZM on performance evolutions of the generated quadrupling millimeter-wave is investigated. Under the practical non-ideal MZM condition, high-quality photonic millimeter-wave could be generated with the optimization. The feasibility of our scheme is verified by theoretical analysis and simulation experiment. For example, with a typical MZM of 30 dB EXT, by setting unbalanced MZM modulation indices m_1 and m_2 to the optimal values, the OSSR and RSSR increased from 14 dB to 45 dB and from 7.8 dB to 39.8 dB, respectively. In addition, for a 2.5 Gbit/s quadrupling RoF transmission system, the receiver sensitivity could be optimized approximately 5.2 dB.

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